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13. ABSTRACT (Maximum 200 words)

The overall goal of the project was to develop a better understanding of plumes in the surface layer of the atmosphere on near-instantaneous time scales. In particular, an extensive database was acquired to characterize the diffusion of surface-level tracer plumes on short time scales for a range of meteorological conditions and amid a variety of surface roughness elements. Empirical and second-order closure methods were tested to predict the diffusion of plumes within 1 km of the source. A computer model was developed and tested to predict concentration fluctuations at fixed receptors located downwind of a ground-level contaminant source. Finally, a dual tracer instrument was developed to simultaneously measure fast-response concentrations of two tracers for use in the field to infer Lagrangian travel times of plume elements.

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concentration fluctuations, instantaneous plume spread, diffusion modeling, fast-response dual tracer analyzer

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A NEW LAGRANGIAN APPROACH TO STUDYING INSTANTANEOUS PLUME DISPERSION AND CONCENTRATION FLUCTUATIONS

FINAL PROGRESS REPORT

MARCH 30, 1998

U.S. ARMY RESEARCH OFFICE

GRANT NUMBER DAAH04-94-G-0349

MONTANA TECH OF THE UNIVERSITY OF MONTANA

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I. INTRODUCTION

Previous research in the atmospheric sciences primarily focused on boundary layer processes with dimensions ranging from theater scales to battlefield scales (Department of the Army 1996). Theater scales in the atmosphere include synoptic weather patterns, while battlefield scales represent mesoscale weather patterns. This project, however, addresses atmospheric phenomena that occur on engagement scales. Engagement scales encompass turbulence, wind field features, and plume behavior with time frames on the order of a few seconds through a few hours. The research is directly relevant to military operations in terms of the effectiveness of smoke obscurants and in terms of the behavior of Nuclear, Biological, and Chemical (NBC) agents from both offensive and defensive standpoints.

The overall goal of the project was to develop a better understanding of plumes in the surface layer of the atmosphere on near-instantaneous time scales. Specific objectives were to: 1) acquire an extensive database of tracer measurements to characterize the diffusion of surface-level plumes on short time scales for a range of meteorological conditions and amid a variety of surface roughness elements; 2) relate instantaneous diffusion of plumes to atmospheric turbulence; 3) estimate Lagrangian travel times from field data for comparison to Eulerian travel times; and 4) incorporate results into a computer model.

The following three sections provide information on how the objectives were addressed. In particular, section II describes fieldwork, while modeling approaches are depicted in section III. The new approach to estimating Lagrangian travel times is explained in Section IV, and Section V summarizes important results from the project. Plans for future work are detailed in section VI. The remainder of the report (sections VII-XII) consists of lists of publications, personnel, awards and honors, inventions, references, and appendices, respectively.

II. EXPERIMENTAL APPROACH

Field campaigns were conducted in 1995, 1996, and 1997, to obtain a database of field measurements of instantaneous plume diffusion, plume meander, and concentration fluctuations. Figure 1 illustrates the basic layout of the experiments. Sulfur hexafluoride (SF_6) tracer was released from a point source located within a meter or two of the surface, and SF_6 concentrations were measured downwind at a rate of 1 Hz using fast-response analyzers. In some tests, an analyzer was installed in a vehicle to collect crosswind concentration profiles while traversing back-and-forth across the plume. In other tests, the analyzer operated at a fixed location while acquiring concentration fluctuation data. Temperature and barometric pressure data were recorded in addition to measurements of wind speed and direction with at least one UVW propeller or sonic anemometer located within a few meters above the roughness surface.

Two sites were used for the field experiments: Galen, Montana; and Boardman, Oregon. Galen is located in a wide, flat, rural valley with grasses and weeds, 0.1-0.3 m in height, as the dominant ground cover. Boardman is also located in a region of flat topography, but the surface roughness consists of approximately 80,000 acres of large blocks of fast-growing poplar trees with uniform canopy height and density. Additional experimental details are presented in Peterson et al. (1998).

Tables A-1through A-4 in the Appendix describe test conditions during a total of 39 experiments at Galen and Boardman. Each experiment was 20-60 min in duration. Source-to-receptor distance ranged from 100 m to approximately 1000 m with most of the tests closer than 500 m. A variety of meteorological conditions were represented. For example, the average wind speed for the Galen site varied between 1.1 and 5.1 ms^{-1}, while for Boardman, the average wind speed was between 0.8 and 2.2 ms^{-1}. The smallest standard deviation of horizontal wind fluctuation was about 10 deg, and the largest, 79 deg. Likewise, the standard deviation of vertical wind fluctuation ranged from approximately 2 deg to 25 deg.

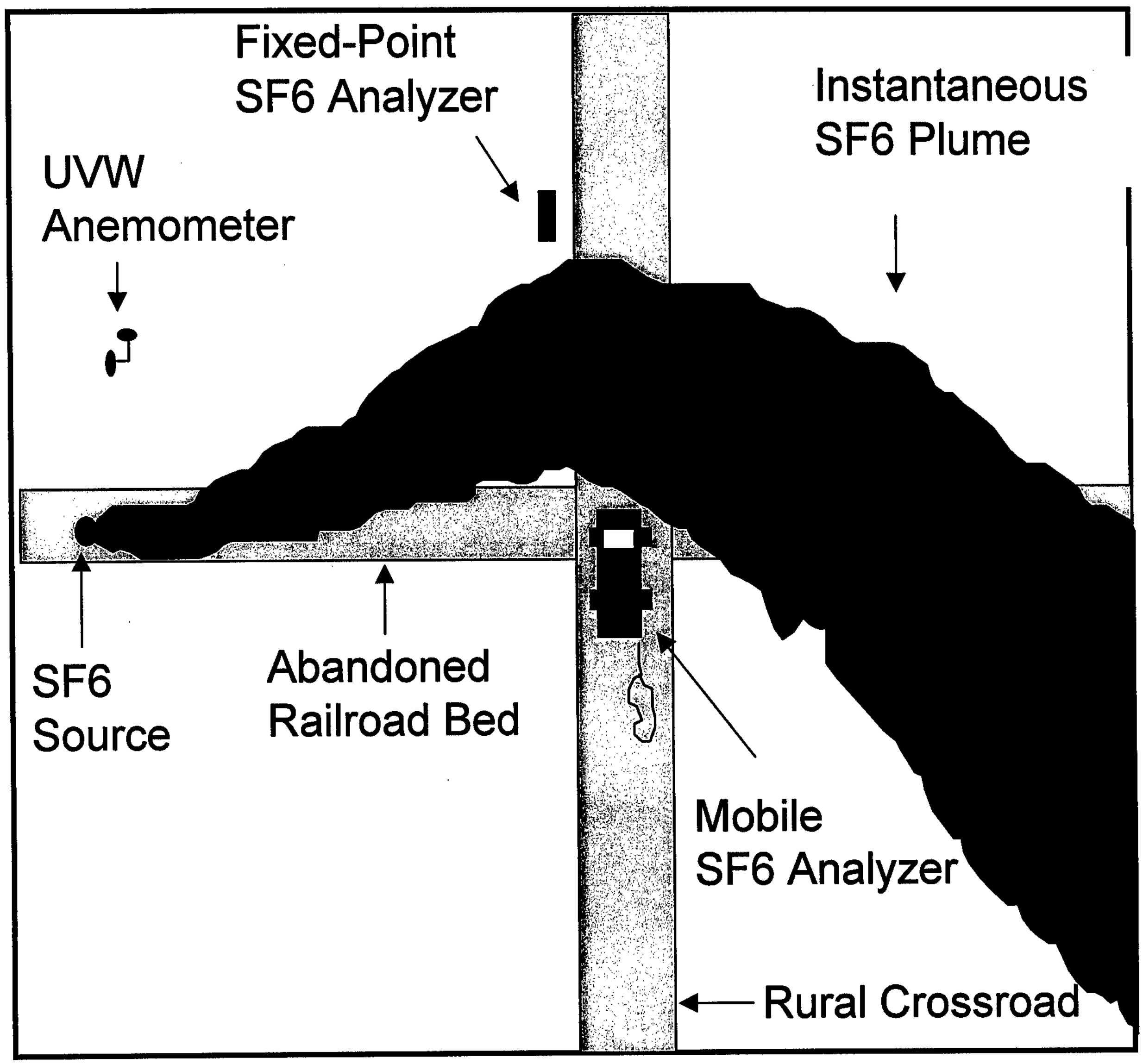

Figure 1. Typical layout of tracer experiments to examine the spread and meander of instantaneous plumes near ground level.

III. MODELING APPROACHES

Two types of modeling were addressed with the Galen and Boardman data: 1) modeling of the spread of instantaneous plumes at downwind distances of approximately 1 km or less; and 2) modeling of concentration fluctuations at fixed receptors. The specific approaches are described below.

A. Instantaneous Plume Spread

The following empirical equations of Peterson and Lamb (1992, 1995) were developed to estimate a diffusion coefficient (σ_i) from basic meteorological parameters measured near source height:

$$\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = 0.222\,\sigma_\theta\, x \qquad \text{(Eq. 1)}$$

$$\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = 0.285\,\sigma_{\theta R}\, x \qquad \text{(Eq. 2)}$$

$$\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = 0.382\,\sigma_\phi\, x \qquad \text{(Eq. 3)}$$

$$\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = 0.402\,\sigma_{\phi R}\, x \qquad \text{(Eq. 4)}$$

$$\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = 0.042\,U_*\, t^{3/2} \qquad \text{(Eq. 5)}$$

where: σ_{yi} is a measure of the horizontal spread of the instantaneous plume in the form of a standard deviation (in units of meters); σ_{zi} is a measure of the vertical spread of the instantaneous plume (in meters); x is the source-to-receptor distance (in meters); σ_θ is the standard deviation of the wind azimuth (in radians); σ_ϕ is the standard deviation of the wind elevation measurements (in radians); $\sigma_{\theta R}$ represents the residual (in radians), in the form of the average standard deviation, between the wind azimuth measurements and a running mean using travel time as the smoothing period; $\sigma_{\phi R}$ is the elevation residual (in radians) also using travel time as a smoothing time; U_* is friction velocity (in m/s); and t is travel time (in seconds). The empirical constants in Equations 1-4 were the result of curve fitting field data from tracer campaigns conducted in the 1980's in Washington State (Peterson and Lamb 1992), and Equation 5 was developed from a small subset of data collected in Canada in 1988 (Peterson and Lamb 1995). The equations have only been tested for downwind distances on the order of 1 km, or less.

While Equations 1-5 represent a turbulence-based approach to estimating instantaneous plume diffusion, a stability-based approach is recommended by Turner (1994). Turner's method involves the following power-law equations for horizontal and vertical plume spread:

$$\sigma_{yi} = a\, x^b \qquad \text{(Eq. 6a)}$$

$$\sigma_{zi} = c\, x^d \qquad \text{(Eq. 6b)}$$

where a, b, c, and d are empirical functions of stability category as shown in Table 1. Turner's coefficients were developed from field data for two downwind distances, 100 m and 4000 m, under unstable, neutral, and very stable conditions. To our knowledge, this method has not been tested elsewhere.

Horizontal and vertical diffusion (σ_{yi} and σ_{zi}) are described by

$$\frac{d\sigma_{yi}^2}{dt} = 2K_{yi}\ , \qquad (7)$$

$$\frac{d\sigma_{zi}^2}{dt} = 2K_{zi} \ , \tag{8}$$

$$\frac{dK_{yi}}{dt} = \sigma_v^2(\ell_y) - A\frac{q_{yi}(\ell_y)}{\ell_y}K_{yi} \, , \tag{9}$$

$$\frac{dK_{zi}}{dt} = \sigma_w^2(\ell_z) - A\frac{q_{zi}}{\ell_z}K_{zi} + \frac{g}{T}G_{zi} \, , \tag{10}$$

and

$$\frac{dG_{zi}}{dt} = C_{w\theta}(\ell_z) - 2bs\frac{q_{zi}}{\ell_z}G_{zi} + \frac{\partial\theta}{\partial z}K_{zi} \, , \tag{11}$$

where A, b, and s are empirical model constants of 0.75, 0.125, and 1.8, respectively. The plume scale energies (q_{yi} and q_{zi}) are defined as

$$q_{yi}^2 = \sigma_u^2\,(\ell_y) + \sigma_v^2\,(\ell_y) + \sigma_w^2\,(\ell_y) \tag{12}$$

$$q_{zi}^2 = \sigma_u^2\,(\ell_z) + \sigma_v^2\,(\ell_z) + \sigma_w^2\,(\ell_z) \tag{13}$$

and the turbulent energy contained in the spectrum for wavelengths shorter than ℓ_y is related to the component velocity variance by

$$\sigma_v^2(\ell_y) = \begin{cases} \overline{v'^2}\left(\dfrac{\ell_y}{\Lambda_y}\right)^{2/3}, & \ell_y \le \Lambda_y \\ \overline{v'^2}, & \ell_y > \Lambda_y \end{cases} \tag{14}$$

where Λ_y is the turbulent length scale. Similar expressions may be written for the u and w velocity variance components by substituting σ_u^2 and $\overline{u'^2}$, or σ_w^2 and $\overline{w'^2}$, for σ_v^2 and $\overline{v'^2}$, respectively, with ℓ_z and Λ_z replacing ℓ_y and Λ_y. The heat flux term, $C_{w\theta}(\ell_z)$, is given by

$$C_{w\theta}(\ell_z) = \begin{cases} \overline{w'\theta'}\left(\dfrac{\ell_z}{\Lambda_z}\right)^{4/3}, & \ell_z \le \Lambda_z \\ \overline{w'\theta'} & \ell_z > \Lambda_z \end{cases} \, , \tag{15}$$

and instantaneous length scales (ℓ_y and ℓ_z) are related to instantaneous plume spread by

$$\ell_y = \min(\alpha_1 \sigma_{yi}, \Lambda_y) \tag{16}$$

and

$$\ell_z = \min(\alpha_1 \sigma_{zi}, \Lambda_z), \tag{17}$$

where α_1 is an empirical constant of 1.25 determined through model testing by Sykes and Gabruk (1997).

Table 1. Power Law Coefficients for $\sigma_{yi} = a\,x^b$ and $\sigma_{zi} = cx^d$ with x in units of meters (from Turner 1994)

Stability Category	A	b	C	d
A	0.18	0.92	0.72	0.76
B	0.14	0.92	0.53	0.73
C	0.10	0.92	0.34	0.72
D	0.06	0.92	0.15	0.70
E	0.045	0.91	0.12	0.67
F	0.03	0.90	0.08	0.64
G	0.02	0.89	0.05	0.61

Few field data exist to test empirical and theoretical methods of predicting instantaneous diffusion coefficients. Prior to this work, Peterson and Lamb (1995) analyzed a small database of plume spread and concentration fluctuations during a field study from 1988. Likewise, Turner (1994) used measurements from only two downwind distances under three stability conditions, and Sykes and Gabruk (1996) reported a limited number of measurements from photographic images of smoke plumes performed by Mikkelsen et al. (1987). Our new measurements from Galen and Boardman provide an independent database for testing Equations 1-6 in addition to the method of Sykes and Gabruk.

B. Concentration Fluctuations

Peterson et al. (1990) and Peterson and Lamb (1995, 1992) formulated a simple meandering plume model to predict real-time concentrations downwind of a surface-based pollutant source. The concept is based on Gifford's meandering plume theory in which time-averaged dispersion is the result of plume meander and relative plume diffusion (Gifford 1959). Wind data near release height are used to predict ground-level concentrations as

$$C_i = \frac{Q}{\pi \sigma_{yi} \sigma_{zi} U_i} e^{\frac{-(\theta_i - \theta_r)^2 (X\pi/180)^2}{2\sigma_{yi}^2}} \qquad \text{(Eq. 18)}$$

where: C_i is instantaneous concentration (in units of $\mu g/m^3$); Q is contaminant release rate (in $\mu g/s$); x is source-to-receptor distance (in meters); U_i is wind speed (in m/s); σ_{yi} is an instantaneous horizontal diffusion coefficient (in meters); σ_{zi} is an instantaneous vertical diffusion coefficient (in meters); Θ_i is a horizontal meander component (in degrees) caclulated as the running average wind direction using travel time as the averaging period; Θ_r is the receptor angular location (in degrees); and (π/180) converts from degrees to meters for a downwind distance x.

The model was packaged by O'Neill (1996a, 1996b) into a user-friendly, windows-based program called **MIND** (the **M**EANDERING **IN**STANTANEOUS **D**IFFUSION MODEL). The **MIND** program uses UVW wind data from on-site measurements to predict concentration time series for arrays of downwind receptors. A smoothing process based on travel time is applied to the wind data as a method of separating wind meander from diffusive elements for each downwind receptor distance, and Equations 1-5 are included as options for estimating instantaneous diffusion coefficients, σ_{yi} and σ_{zi}. The program also calculates concentration fluctuation statistics, such as: mean concentration; intensity (the ratio of concentration standard deviation to mean concentration); peak-to-mean ratio; and intermittency factor (the fraction of time non-zero concentrations are observed at a receptor). Results are presented graphically in a Visual Basic format.

Galen and Boardman measurements of winds and concentration fluctuations at fixed-point receptors provide field data for comparison to model predictions from MIND. Section V contains a summary of model testing conducted to date.

IV. DUAL TRACER APPROACH FOR ESTIMATING LAGRANGIAN TRAVEL TIMES

A novel experimental method was developed and tested to measure Lagrangian travel times for dispersing tracer plumes (Peterson et al. 1995). The idea is to release one tracer into the atmosphere at a constant rate from a point source, while releasing another tracer at a rate which increases linearly in time. The concentration ratio of the two compounds at any downwind distance will infer the time of release, and hence, the Lagrangian transport time will be the elapsed time between release and measurement.

In order to test this concept, the following equipment was designed and constructed for the project: 1) a computer-controlled release system capable of releasing and monitoring two tracer gases; and 2) a dual tracer analyzer capable of simultaneously measuring ambient concentrations of two tracer gases on near-instantaneous time scales. These instruments are described as follows.

A. Computer-Controlled Dual Tracer Release System

The new computer-controlled release system was designed to emit two tracer gases, sulfur hexafluoride (SF_6) and perfluoromethylcyclohexane (PMCH). The fan of a space heater blows warm air through a rectangular section of galvanized steel duct, 15 cm by 15 cm, and out a baffled expansion, 76 cm by 76 cm at the exit. Sulfur hexafluoride, a gas at ambient pressure and temperature, is supplied to the duct from a compressed gas cylinder via a mass-flow controller valve. Perfluoromethylcyclohexane, a liquid at ambient conditions, is vaporized into the airstream by pumping liquid PMCH from a reservoir (a medical IV bag), through a hypodermic needle, and onto a hotplate located within the duct. The temperature of the airflow within the ductwork is maintained above the boiling point of PMCH (76 °C). A portable, notebook computer with LABVIEW software (by National Instruments) was programmed to control and monitor the release of the tracers. The release system was also designed to monitor meteorological conditions near the source via fast-response temperature sensors and an anemometer. Additional design information is presented by Peterson et al. (1995) and Ballard (1995).

B. Dual Tracer Analyzer

1. Instrument Description

The dual tracer analyzer (DT1) employed in this project was based upon the original dual tracer instrument described by Rydock (1992) (see Rydock and Lamb, 1994). In this work, sulfur hexafluoride (SF6) and perfluoromethylcyclohexane (PMCH) were used as tracer gases. The instrument was constructed at WSU and, during this project, various changes in the instrument design and operation were tested in an attempt to improve instrument performance. The basic instrument design is a modification of the single tracer analyzer (Benner and Lamb, 1985). In the dual tracer analyzer, sample air is mixed with hydrogen in a catalytic reactor where oxygen in the sample flow is combusted to form water. The wet sample stream is then dried in a countercurrent Nafion drier. The dry sample stream is split with one stream flowing directly to an electron capture detector (ECD1) where the combined presence of the SF_6 and perfluorocarbon tracers cause a response. The second sample stream is directed through an adsorbent trap which removes the perfluorocarbon tracer, but allows the SF_6 tracer to pass through to ECD2. The concentration of SF_6 is obtained from ECD2 directly, while the concentration of PMCH is obtained by difference between ECD1 and ECD2. The instrument pump and flow controller are located downstream of the ECDs to minimize dead volume and thus optimize the instrument response time. The DT1 instrument also included a manual switching valve to allow one trap to be switched into the flow stream while a second trap was positioned in a heat and purge mode. By cleaning one trap while using the other trap, nearly continuous operation could be attained. A schematic of the instrument is shown in Figure 2 and the response of the instrument to SF6 and PMCH is shown in Figure 3.

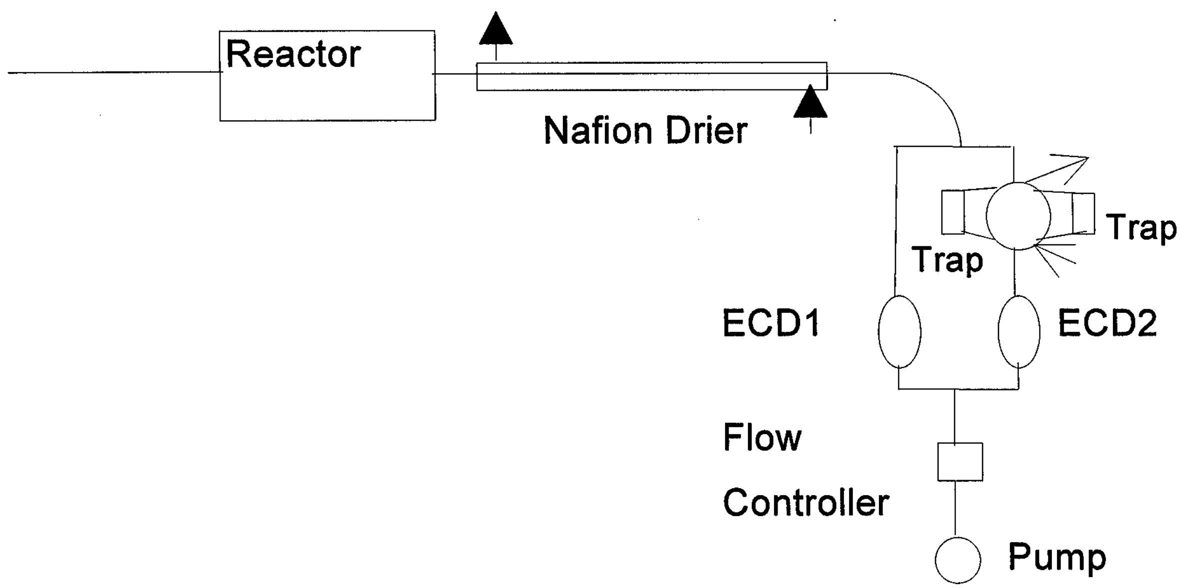

Figure 2. Schematic of the dual tracer analyzer.

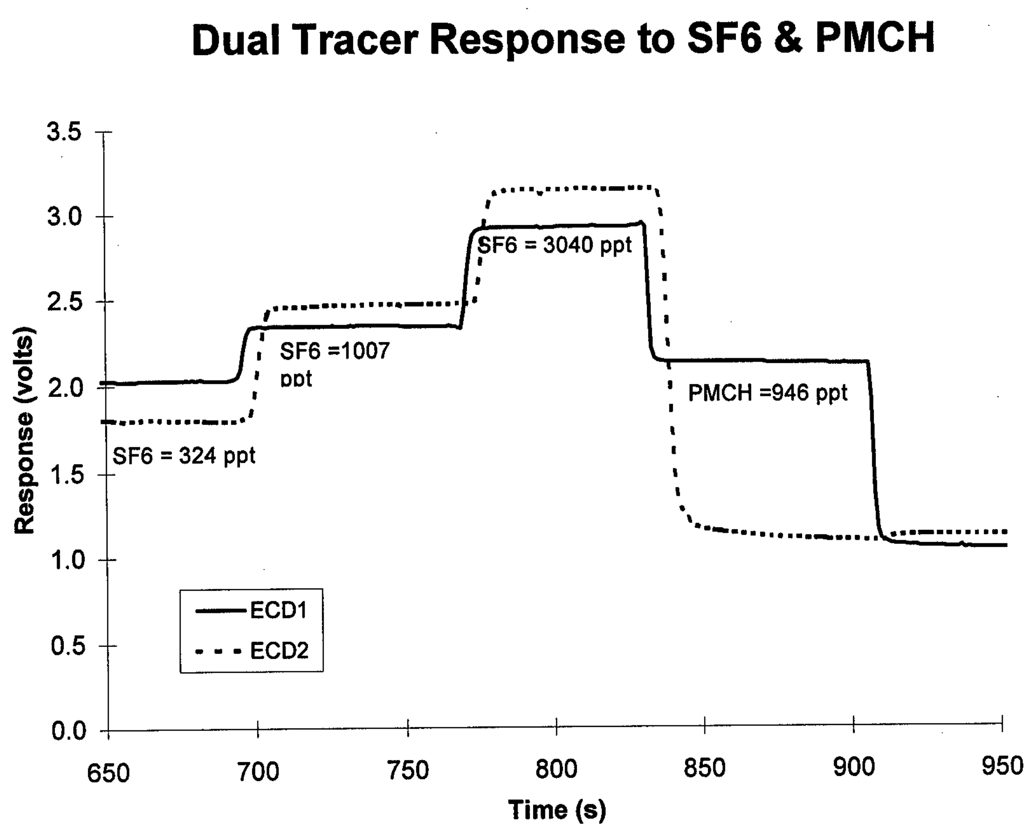

Figure 3. Response of dual tracer instrument to SF_6 and PMCH tracers.

2. Instrument Modifications

In the initial tests of the instrument, it was found that the original alumina traps prescribed by Rydock were very sensitive to the presence of moisture and became ineffective after a relatively short period of use. Subsequently, these traps were replaced with commercial traps (Supelco, Inc., Carbosieve 400) which appeared to yield satisfactory performance. Similarly, the original ECDs employed tritium foil radioactive β sources which were operated at either ambient or relatively low (100 °C) temperatures. Because of differences in response and signal drift, these detectors were replaced with commercial Ni^{63} ECDs (Valco, Inc.) and operated at elevated, constant temperatures (typically 250 °C). Because of the difficulties associated with decomposing the two ECD signals to yield PMCH concentrations, a version of the instrument was also tested which employed a computer-controlled constant frequency switching valve and a single ECD. This was designed to reduce problems due to differences in detector responses, but the resulting AC signal introduced other uncertainties in the deconvolution of the signal and the instrument response time was degraded as well. As a result, the instrument was converted back to a dual detector configuration.

3. Instrument Calibration

The instrument was calibrated frequently during every field period using a series of commercial gas mixtures (Scott-Marrin, Inc., certified accuracy ±5%). These mixtures included SF_6 in air at concentrations ranging from approximately 300 ppt to 10 ppb and PMCH at concentrations near 1000 ppt. Standards were introduced by flowing standard gas through a tee connected to the analyzer inlet at a flow rate which slightly exceeded the sample inlet flow (typically 70 cm^3/min). Typical results from a calibration are shown in Figure 4. The response for both detectors was represented by a power law best fit:

$$C1_{SF6} = a\Delta V_1^{b} \qquad (19)$$

$$C1_{PMCH} = c\Delta V_1^{d} \qquad (20)$$

$$C2_{SF6} = e\Delta V_2^{f} \qquad (21)$$

where ΔV is the change in signal voltage for the indicated detector (1 or 2) relative to the detector baseline voltage, and a through e are the best-fit power law coefficients for each case. In some cases, the power law fit did not appear to match the change in response at high concentrations (>3 ppb). In these cases, a linear fit was used above 1 ppb. Given these measured calibration curves, the concentration of PMCH in an unknown sample stream is obtained by determining the SF_6 present from the response of detector 2, rearranging (1) to find the response in detector 1 due to the SF_6 concentration, subtracting this response from the measured voltage change in detector 1, and then applying (2) to the remaining voltage response:

$$C2_{SF6} = e\Delta V_2^{f} \qquad (22)$$

$$\Delta V_{1SF6} = (C2_{SF6}/a)^{1/b} \tag{23}$$

$$\Delta V_{1PMCH} = \Delta V_{1total} - \Delta V_{1SF6} \tag{24}$$

$$C_{1PMCH} = c\Delta V_{1PMCH}^{d} \tag{25}$$

or

$$C_{1PMCH} = c\{\Delta V_{1total} - [(e\Delta V_2^{f})/a]^{1/b}\}^{d} \tag{26}$$

Because of the sensitivity of the results to the power law exponents, the application of this calculation to determine PMCH concentrations is very dependent upon the goodness of fit of the regression curve to the calibration points. This sensitivity yields a much larger uncertainty in PMCH concentrations than in the SF_6 concentrations. In addition, a complete series of PMCH standard mixtures covering the range of concentrations of interest was not readily available, and the availability of SF_6 mixtures at only 1000, 3000, and, during some test, 10,000 ppt was probably insufficient to completely specify the non-linear portion of the SF_6 calibration curve.

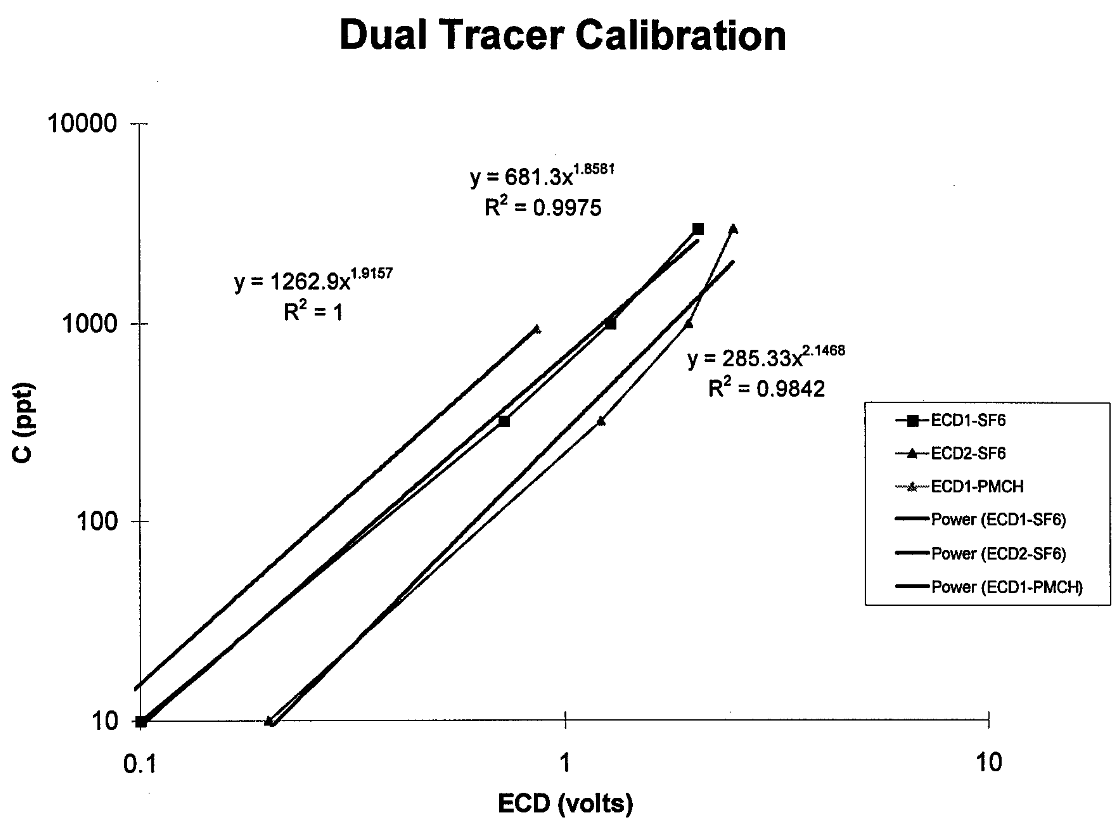

Figure 4. Calibration results and best-fit power law curves for SF_6 and PMCH.

4. Instrument Delay and Time Response

The instrument delay or lag time is taken as the time from when a step change in concentration is introduced at the sample inlet until a change in detector voltage is first identified. This delay time depends upon the sample flow rate and the total dead volume along each flow path. The delay times were approximately 4 s different between the no-trap (ECD1) and trap (ECD2) channels.

The instrument response time is defined as the time for the signal to reach 63% of full scale due to a step change in concentration (1/e rise time). It is associated with longitudinal diffusion and mixing along the flow path. The instrument response time acts as a filter on high frequency fluctuations of concentration in the atmosphere. It is important to document the response time in order to interpret peak instantaneous concentrations correctly. As shown in Figure 5, the response time was slower for the trap channel compared to the no-trap channel due to the mixing inherent in flow through the adsorbent trap.

It is important to understand the implications of these differences in the time characteristics of the SF6 and PMCH signals. The delay time can be corrected quite simply by adjusting the faster channel with respect to the slower channel. However, the difference in response time requires filtering the faster channel to match the response from the slower channel in order to examine the instantaneous behavior of the ratios of concentrations. This can be accomplished by assuming that the detectors can be approximated as RC filters in an electronic circuit.

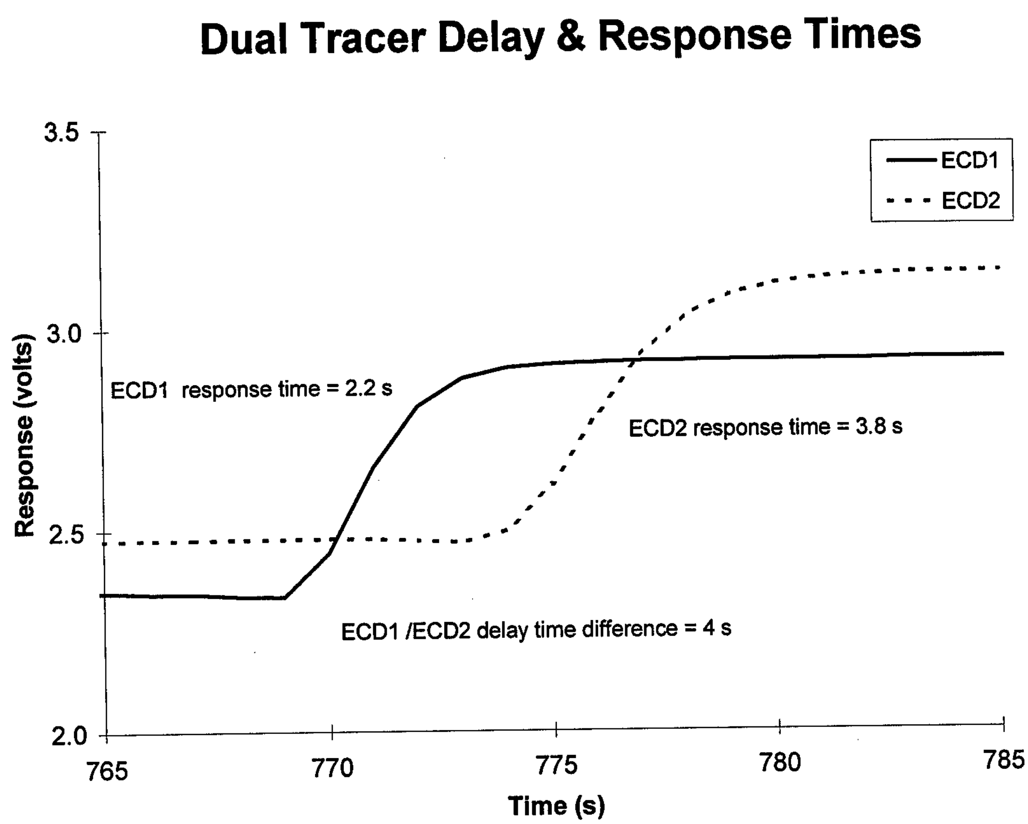

Figure 5. Instrument delay and response times for step change in tracer gas concentrations.

5. Data Acquisition & Signal Processing

In the initial field tests, the signals from the instrument were recorded using a laptop computer connected to an external data acquisition card (PPIO8). A Quickbasic program was written to acquire the signals, record location codes entered by the operator to track the vehicle position, and plot the signals in real-time. In the final field tests, the external card was replaced with a Tempbook data acquisition system (Omega, Inc). In all cases, the data system recorded signals at 1 Hz and the data were stored on the computer hard drive and also on floppy disks. Calibrations results were obtained in the same manner.

V. SUMMARY OF MOST IMPORTANT RESULTS

A. Plume Spread

Tables A-5 through A-6 contain diffusion coefficients for the Galen and Boardman experiments. The data are summarized in terms of σ_i values from the moment method for traverse data, from the centerline method for traverse and fixed-point data, from Eqs. (1)-(6), and from the second-order closure method. Described in Peterson et al. (1998), the moment method produces a horizontal diffusion coefficient (σ_{yi}) from plume traverse data by integrating the "concentration versus crosswind distance" curve. On the other hand, the centerline method utilizes the maximum concentration at a fixed receptor, or along a plume traverse, to represent the instantaneous plume centerline concentration (C_{cl}), and a Gaussian formulation estimates a diffusion coefficient for ground-level plumes from $\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5} = Q(\pi C_{cl} U)^{-1}$, where Q is release rate of the tracer and U is wind speed near source height. The centerline method is much less sensitive than the moment method to uncertainties such as instrument response, plume meander, and source-to-receptor configuration (Peterson et al. 1998)

Figures 6-12 compare predicted diffusion coefficients to observed values from the centerline method. Overall, most of the predicted data fall within 1:2 and 2:1 lines-of-correspondence, and Table 2 summarizes model performance in terms of a few simple statistics.

As illustrated in the Fig. 6, Eq. (1) has a tendency to overpredict the diffusion coefficient in the Galen experiments. Equation (2), depicted in Fig. 7, produces the average ratio (of predicted-to-observed) nearest 1.0 with the least amount of bias for both Galen and Boardman data. Equations (3) and (4) underpredict the plume spread in approximately 75-80 % of the tests, and Figs. 8 and 9 portray this bias. In Fig. 10, Eq. (5) generates the largest number of outliers between 3 and 4; it also underestimates the diffusion coefficient in 25 of the 29 experiments. Turner's simple power-law equations predict values that are very similar to the turbulence-based methods, and the results in Fig. 11 exhibit an inclination to underpredict. Lastly, Figure 12 shows that Sykes' second order approach produces diffusion coefficients comparable to the observed values with a slight bias toward underestimating.

Regarding the use of these equations in regulatory applications, Eq. (2) appears to perform the best, but Eqs. (1) and (3) utilize standard meteorological parameters (σ_θ and σ_ϕ) that could easily be incorporated into existing dispersion models. The technique of Turner coincides with the stability-based methods currently used in models such as ISC and SCREEN. Finally, the theoretical approach of Sykes and Gabruk (1997) provides diffusion estimates that are very similar to values from the simpler empirical methods. Overall, any of the methods appear to be robust, with the exception of Eq. (5), when compared to field data in the Galen and Boardman experiments.

Table 2. Summary of Performance for Galen and Boardman Diffusion Data

Equation	Average Ratio P:O	Standard Deviation P:O	% Ratios ≥ 0	% Ratios < 0
Equation 1	1.19	0.52	58.6	41.4
Equation 2	1.00	0.31	51.7	48.3
Equation 3	0.81	0.21	24.1	75.9
Equation 4	0.78	0.21	20.7	79.3
Equation 5	0.66	0.40	13.7	86.2
Turner's Equations	0.99	0.46	37.9	62.1
Sykes' Approach	0.85	0.28	42.1	57.9

P:O – ratio of predicted diffusion coefficient to the observed value.

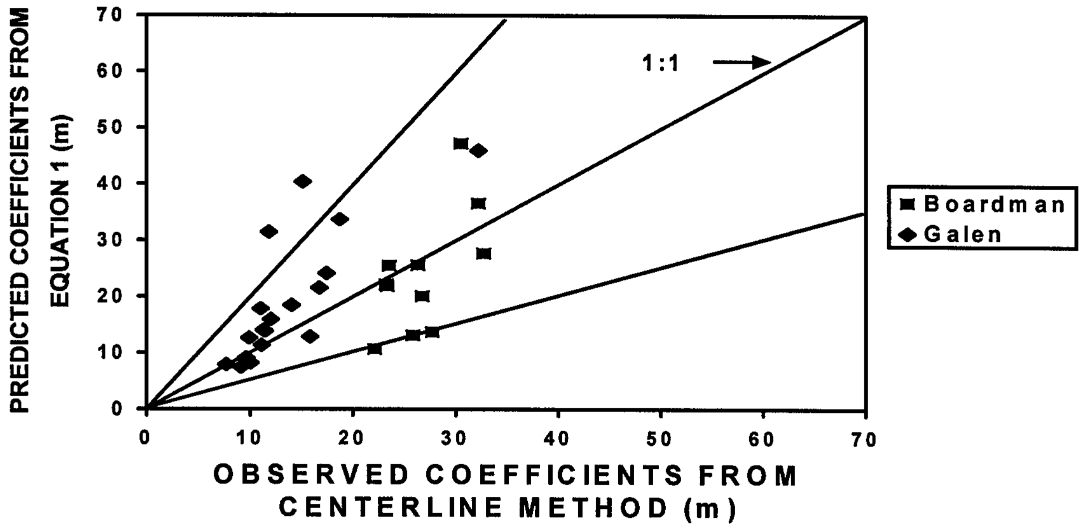

Figure 6. Predicted diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Equation 1 is $\sigma_i = 0.222\,\sigma_\theta\,x$.

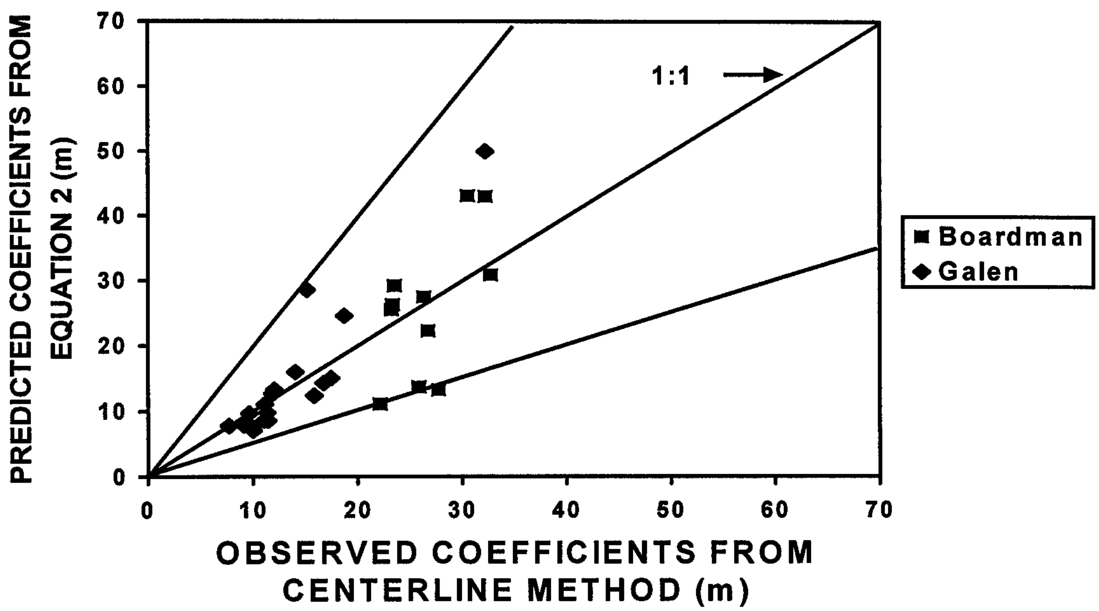

Figure 7. Predicted diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Equation 2 is $\sigma_i = 0.285\,\sigma_{\theta R}\,x$.

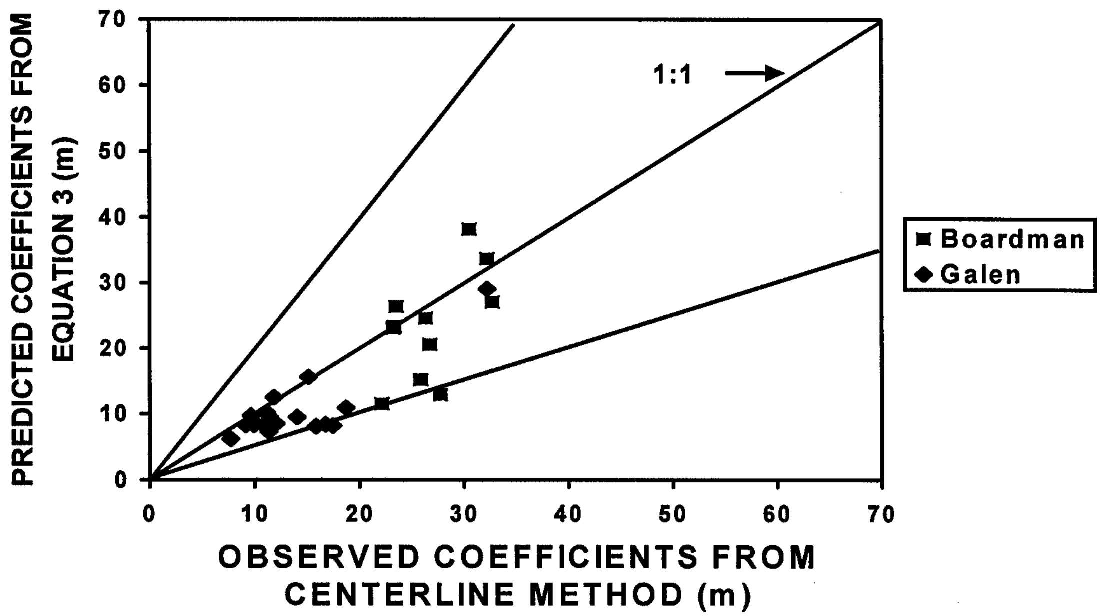

Figure 8. Predicted diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments Equation 3 is $\sigma_i = 0.382\ \sigma_\phi\ x$.

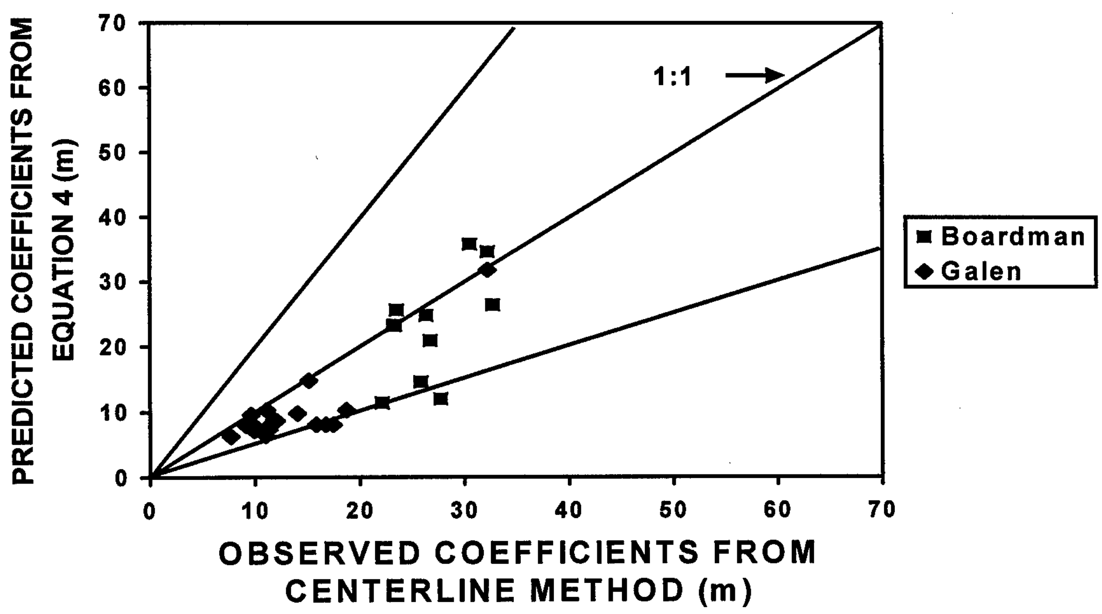

Figure 9. Predicted diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Equation 4 is $\sigma_i = 0.402\ \sigma_{\phi R}\ x$.

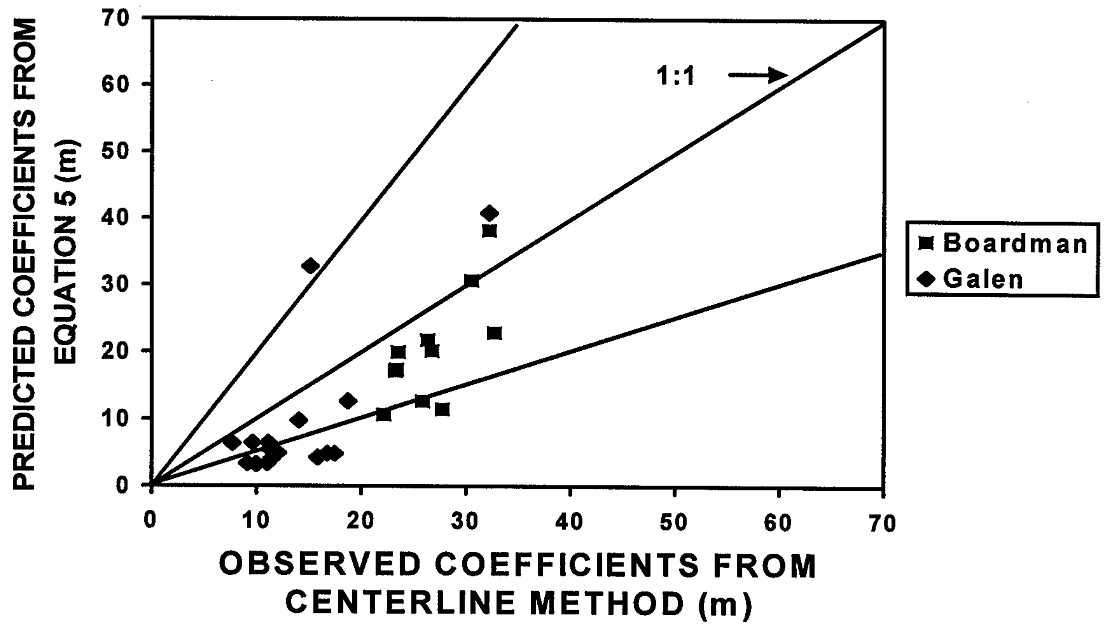

Figure 10. Predicted diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Equation 5 is $\sigma_i = 0.042\, U \cdot t^{3/2}$.

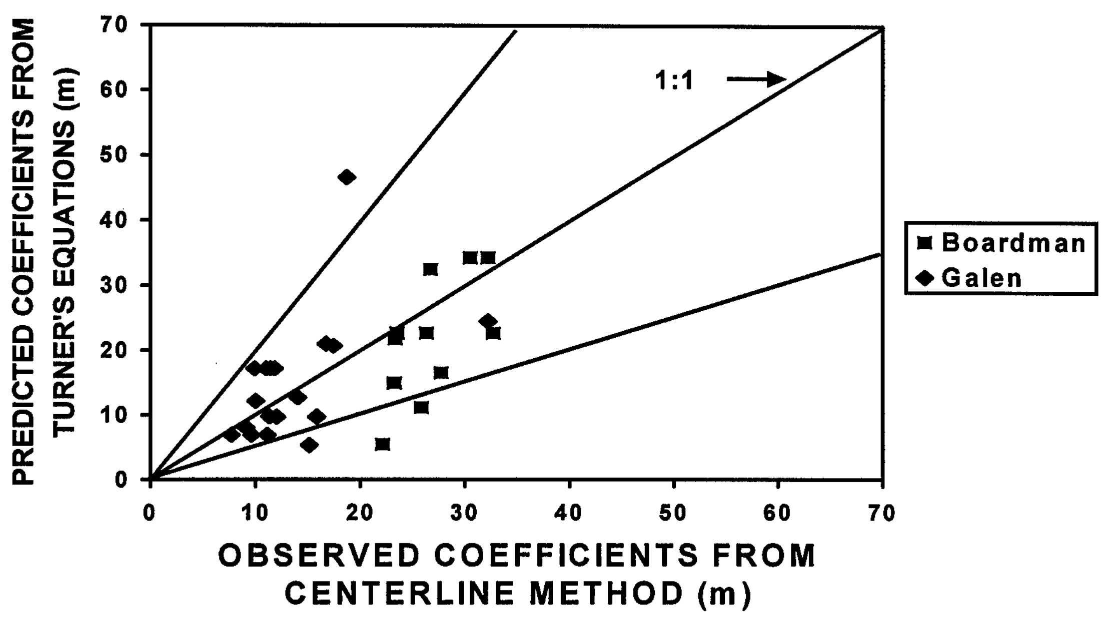

Figure 11. Predicted horizontal diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Turner's power-law equations were used to estimate $\sigma_i = (\sigma_{yi}\,\sigma_{zi})^{0.5}$.

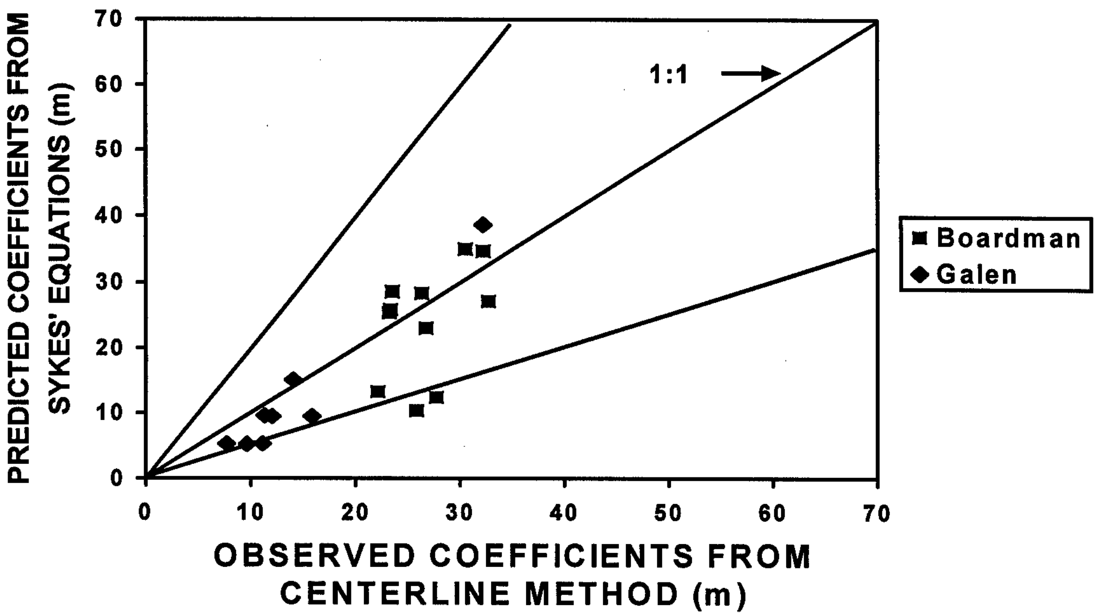

Figure 12. Predicted horizontal diffusion coefficients versus observed diffusion coefficients for the Galen and Boardman experiments where Sykes' second-order closure method was used to estimate $\sigma_i = (\sigma_{yi}\sigma_{zi})^{0.5}$.

B. Concentration Fluctuations

Figure 13 illustrates the ability of the MIND model to predict instantaneous concentration exposure downwind of a ground-level source. The downwind distance for this test (S806e) is 100 m; the average wind speed is 2.5 m/s; and the standard deviation of horizontal wind fluctuation is 21.2 deg. The model is able to match the low-frequency fluctuations in response to plume meander, and it is able to simulate the magnitude of the concentrations in response to diffusion. In terms of time series statistics, the observed and predicted mean concentrations are 1763 ppt and 2417 ppt, respectively; the peak-to-mean ratios are 9.26 and 6.68; the intermittency factors are 0.40 and 0.60; and the concentration intensities are 1.83 and 1.77.

Tables A-7 through A-11 contain results of model testing for all Galen 1996 and 1997 experiments. The simulations were performed with MIND using Equations (1)-(5) to predict the diffusion coefficients. Figures 14-18 depict these results in comparison to the observed values from the tracer data, and Table 3 summarizes model performance in terms of average concentration, peak concentration, peak-to-mean ratio, intermittency factor, and concentration intensity. On average, the model predicts most of the concentration statistics within a factor of two or better when Eqs. (1)-(4) are used to predict the plume spread. Results from MIND using Eq. (5), however, exhibit a notably larger tendency to overestimate average and peak concentrations.

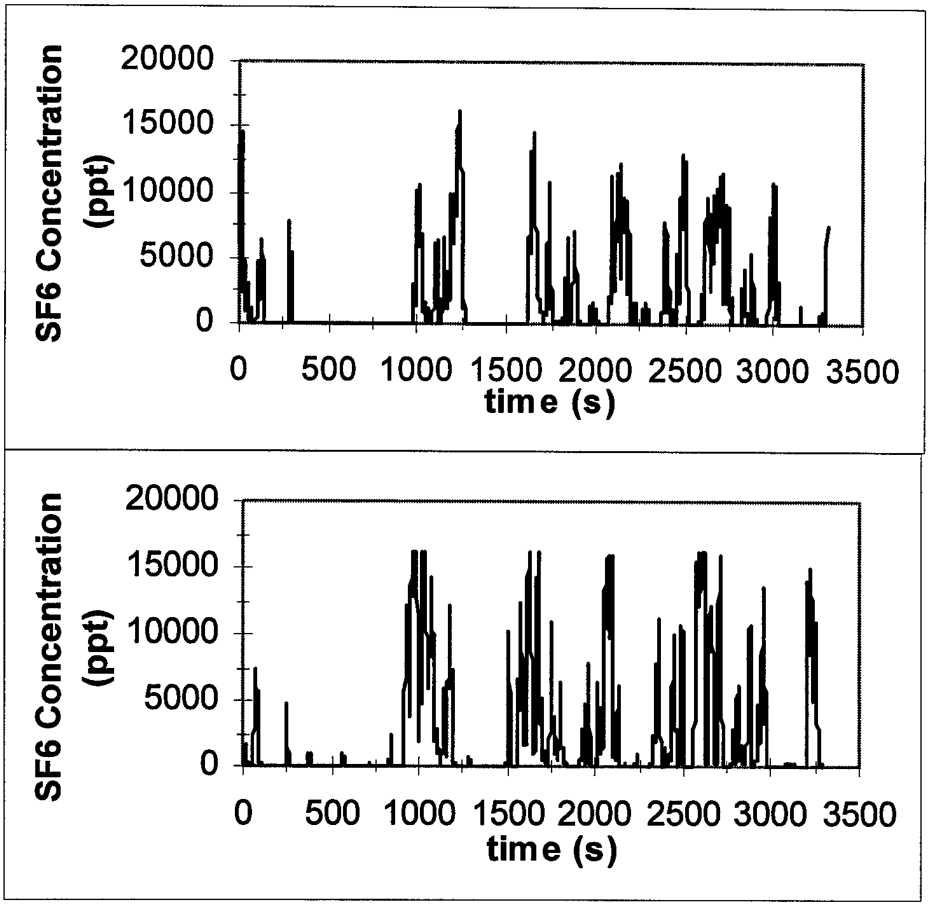

Figure 13. An example of the performance of the MIND model. The top figure contains tracer data from the field during Galen Test S806e, and the bottom figure depicts predicted concentrations from MIND.

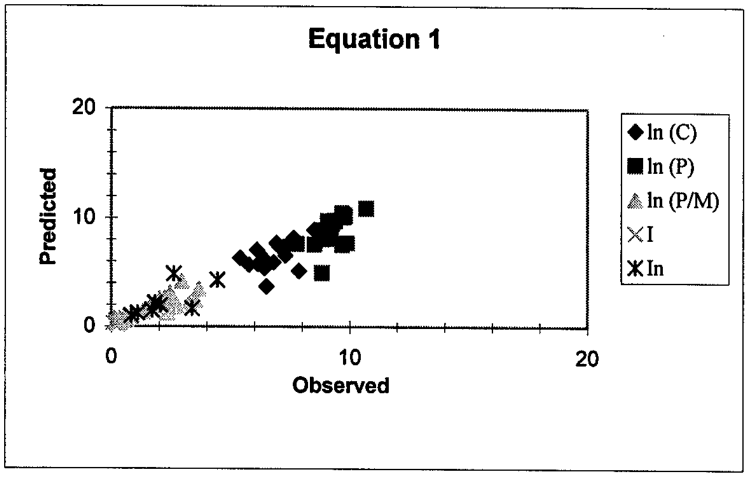

Figure 14. Predicted versus observed concentration fluctuation statistics (using Equation 1 in the MIND model) for Galen 1996 and 1997 experiments with C = concentration mean (ppt), P = concentration peak (ppt), P/M = peak-to-mean ratio, I = intermittency factor, and In = concentration intensity.

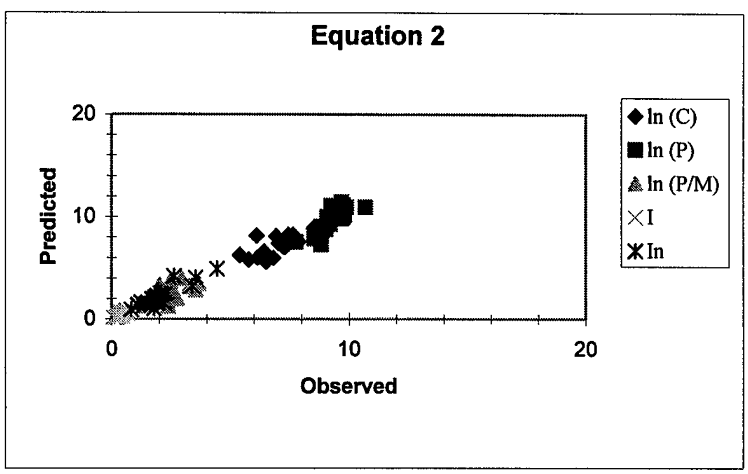

Figure 15. Predicted versus observed concentration fluctuation statistics (using Equation 2 in the MIND model) for Galen 1996 and 1997 experiments with C = concentration mean (ppt), P = concentration peak (ppt), P/M = peak-to-mean ratio, I = intermittency factor, and In = concentration intensity.

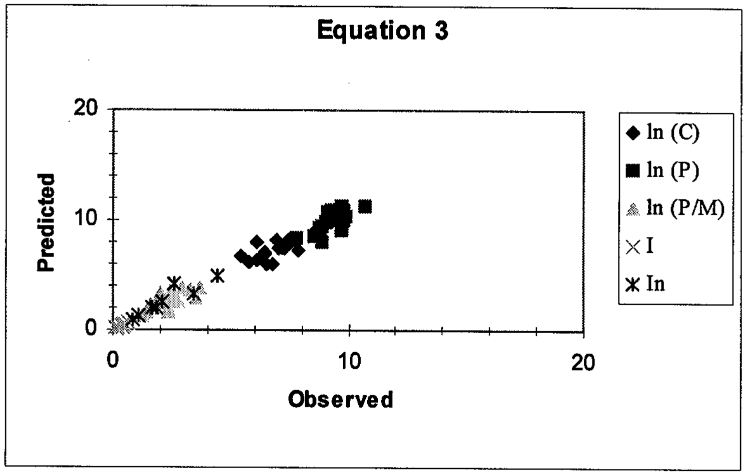

Figure 16. Predicted versus observed concentration fluctuation statistics (using Equation 3 in the MIND model) for Galen 1996 and 1997 experiments with C = concentration mean (ppt), P = concentration peak (ppt), P/M = peak-to-mean ratio, I = intermittency factor, and In = concentration intensity.

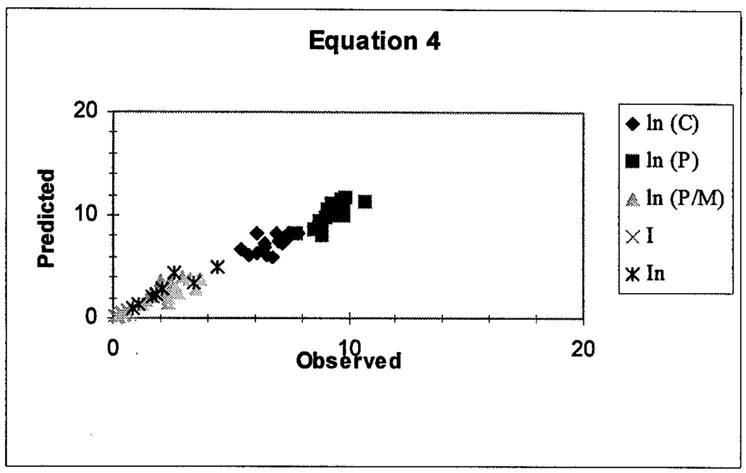

Figure 17. Predicted versus observed concentration fluctuation statistics (using Equation 4 in the MIND model) for Galen 1996 and 1997 experiments with C = concentration mean (ppt), P = concentration peak (ppt), P/M = peak-to-mean ratio, I = intermittency factor, and In = concentration intensity.

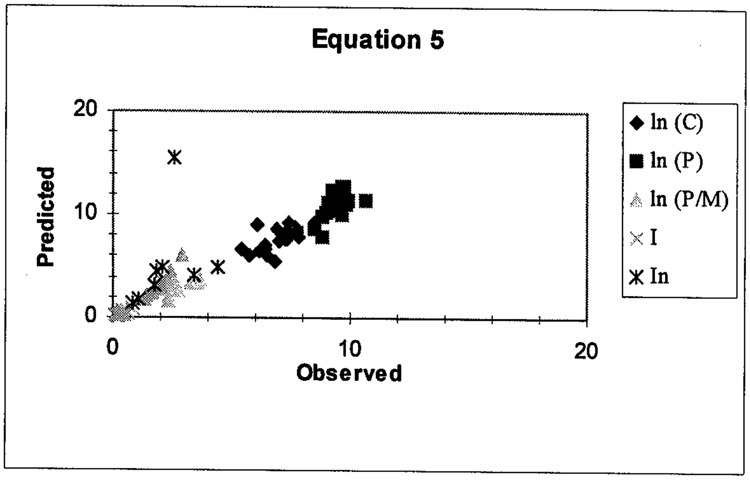

Figure 18. Predicted versus observed concentration fluctuation statistics (using Equation 5 in the MIND model) for Galen 1996 and 1997 experiments with C = concentration mean (ppt), P = concentration peak (ppt), P/M = peak-to-mean ratio, I = intermittency factor, and In = concentration intensity.

Table 3. Summary of MIND Model Performance for Galen 1996 and 1997 Experiments

Equation for σ_i	Average Ratio C_p:C_o	Average Ratio P_p:P_o	Average Ratio P/M_p:P/M_o	Average Ratio I_p:I_o	Average Ratio In_p:In_o
Eq. 1	1.7 (±1.7)	1.8 (±1.4)	1.3 (±1.0)	1.2 (±0.7)	1.1 (±0.3)
Eq. 2	1.9 (±1.5)	2.2 (±1.1)	1.5 (±0.8)	1.0 (±0.4)	1.2 (±0.3)
Eq. 3	1.2 (±0.8)	1.0 (±0.7)	1.0 (±0.8)	1.4 (±0.7)	0.9 (±0.3)
Eq. 4	2.1 (±1.9)	2.8 (±1.8)	1.7 (±1.1)	1.0 (±0.4)	1.2 (±0.2)
Eq. 5	3.1 (±4.2)	6.3 (±6.4)	3.5 (±5.7)	0.8 (±0.4)	1.7 (±1.1)

(± Standard Deviation)
C_p:C_o - Predicted concentration mean : Observed mean
P_p:P_o - Predicted Peak : Observed peak
P/M_p:P/M_o - Predicted peak-to-mean : Observed peak-to-mean
I_p:I_o - Predicted intermittency factor : Observed intermittency factor
In_p:In_o - Predicted concentration intensity : Observed intensity.

VI. PLANS FOR FUTURE WORK

Research on instantaneous plume diffusion, plume meander, and concentration fluctuations will continue at Montana Tech. In particular, additional experiments will be conducted to fine-tune the new dual tracer technique for investigating travel time of plume events, and measurements will focus on plume diffusion in the "stable" boundary layer. Few field data are currently available to relate short-term plume characteristics to turbulence and to wind field features under stable meteorological conditions with low wind speeds. The following specific objectives will be met: 1) two extensive tracer campaigns will be conducted during nighttime hours with dual tracer releases and single tracer releases; 2) concentration data will be processed and analyzed from fast-response analyzers located within several km of the source; 3) relative diffusion coefficients, concentration fluctuation statistics, travel time, and plume meander will be related to on-site wind data from fast-response anemometers and from an acoustic sounder; 4) the MIND model will be evaluated (and modified) for stable conditions; and 5) the field measurements will be compiled into a database that will be available to other researchers or engineers.

VII.LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

A. Peer-Reviewed Papers

1. Peterson, H. and B. Lamb, 1995: Instantaneous diffusion and concentration fluctuations. *Journal of Applied Meteorology*, **31**, 553-564.

2. Peterson, H., D. Mazzolini, S. O'Neill, and B. Lamb, 1998: Instantaneous spread of plumes in the surface layer. *Journal of Applied Meteorology*, in press.

3. O'Neill, S., B. Lamb, H. Peterson, and T. Donovan, 1998: Concentration fluctuations and peak-to-mean ratios. *Journal of Applied Meteorology*, in preparation (to be submitted during spring of 1998).

B. Published Conference Abstracts

1. Donovan, T. and H. Peterson, 1997: Comparison of measured concentration fluctuations to data from a meandering diffusion model. *Preprints of the 12th Symposium on Boundary Layers and Turbulence*, 28 July – 1 August 1997, Vancouver, BC, by the AMS, pp. 120-121.

2. Mazzolini, D., 1996: An investigation of diffusion of instantaneous plumes. *Preprints of the Ninth Joint Conference on the Applications of Air Pollution Meteorology with AWMA*, 28 January – 2 February 1996, Atlanta, GA, by the AMS, Boston, MA, pp. 351-354.

3. Mazzone, C. and H Peterson, 1997: An investigation of probability distributions for concentration fluctuation data. *Preprints of the 12th Symposium on Boundary Layers and Turbulence*, 28 July – 1 August 1997, Vancouver, BC, by the AMS, pp. 122-123.

4. O'Neill, S., 1996: Development and testing of a model for instantaneous plume diffusion. *Preprints of the Ninth Joint Conference on the Applications of Air Pollution Meteorology with AWMA,* 28 January – 2 February 1996, Atlanta, GA, by the AMS, Boston, MA, pp. 364-367.

5. Peterson, H., 1997: A tracer laboratory for undergraduate environmental engineering programs. *Preprints of the ASEE 1997 Conference,* 15 June – 18 June 1997, Milwaukee, WI, by the ASEE, Washington, DC, CDROM.

6. Peterson, H. and B. Lamb, 1996: A tracer approach to investigating plume diffusion and turbulence. *Preprints of the Ninth Joint Conference on the Applications of Air Pollution Meteorology with AWMA,* 28 January – 2 February 1996, Atlanta, GA, by the AMS, Boston, MA, pp. 37-40.

7. Peterson, H., P. Ballard, and B. Lamb, 1995: A new Lagrangian approach to studying instantaneous plume dispersion and concentration fluctuations. *Preprints of the 11th Symposium on Boundary Layers and Turbulence,* 27 March – 31 March 1995, Charlotte, NC, by the AMS, Boston, MA, pp. 140-143.

8. Peterson, H., S. O'Neill, and B. Lamb, 1997: A simple approach for estimating short-term peak concentrations with time-averaged models. *Preprints of the 12th Symposium on Boundary Layers and Turbulence,* 28 July – 1 August 1997, Vancouver, BC, by the AMS, pp. 112-113.

C. Master of Science Theses

1. Ballard, P., 1995: *Design and Testing of Release Equipment and Analytical Methods for Examining the Instantaneous Dispersion of Atmospheric Plumes*, Master of Science thesis, Montana Tech, Butte, MT.

2. Donovan, T., 1998: *A Comparison of Measured Plume Concentrations to Predictions from a Meandering Plume Model.* Master of Science thesis, Montana Tech, Butte, MT.

3. Joshi, N., 1998: *An Investigation of Instantaneous Plume Spread Under Neutral through Extremely Stable Conditions*. Master of Science thesis, Montana Tech, Butte, MT.

4. Mazzolini, D., 1996: *An Investigation of the Diffusion of Instantaneous Plumes*. Master of Science thesis, Montana Tech, Butte, MT.

5. O'Neill, S., 1996: *The Meandering Instantaneous Diffusion (MIND) Model.* Master of Science thesis, Montana Tech, Butte, MT.

VIII. LIST OF ALL PARTICIPATING PERSONNEL (including degrees earned)

A. Faculty

1. Dr. Holly G. Peterson, Associate Professor, Environmental Engineering Department, Montana Tech, Butte, MT (summer salary only).

2. Dr. Brian Lamb, Boeing Distinguished Professor, Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

B. Staff

1. Allwine, Eugene, Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

3. Chin, King Hong, Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

2. Worthington, Richard, Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

C. Undergraduate Students

1. Donovan, Tina (MT Tech - Bachelor of Science Degree obtained in Environmental Engineering, 1997).

2. Jenkins, Fred (MT Tech - Bachelor of Science Degree in Engineering Science, 1996). Note: Fred only assisted in equipment development during one month of the project.

3. Kirkpatrick, Denise (MT Tech - Bachelor of Science Degree obtained in Environmental Engineering, 1995).

4. LaPlaunt, Brian (MT Tech - Bachelor of Science Degree obtained in Environmental Engineering, 1995).

5. Mazzolini, Dione (MT Tech - Bachelor of Science Degree obtained in Environmental Engineering, 1995).

D. Graduate Students

1. Ballard, Patrick (MT Tech - Master of Science Degree obtained in Environmental Engineering, 1995).

2. Donovan, Tina (MT Tech - Master of Science Degree will be completed in Environmental Engineering, 1998).

3. Hilker, Greg (MT Tech - Master of Science Degree obtained in Engineering Science, 1996). Note: Greg only assisted in equipment development during one month of the project.

4. Joshi, Nalin (MT Tech - Master of Science Degree will be completed in Environmental Engineering, 1998). Note: Nalin has been funded elsewhere for his project, but he has been analyzing data from, and directly related to, this project.

5. Mazzolini, Dione (MT Tech - Master of Science Degree obtained in Environmental Engineering, 1996).

6. Mazzone, Charles (MT Tech - Master of Science Degree should be in Environmental Engineering, 1998).

7. O'Neill, Susan (MT Tech - Master of Science Degree obtained in Environmental Engineering, 1996).

8. Peterson, Mark (MT Tech - Master of Science Degree will be completed in Environmental Engineering, 1998). Note: Mark only assisted in fieldwork and data analysis during one month of the project.

9. Thomas, Richard (MT Tech - Master of Science Degree will be completed in Environmental Engineering, 1998). Note: Richard only assisted in fieldwork and data analysis during one month of the project.

10. Finn, Dennis (WSU - Ph.D. completed in Civil Engineering, 1996).

IX. AWARDS AND HONORS

A. Faculty

1. Dr. Holly Peterson: **Coeur d'Alene Mines Corporation Faculty Achievement Award, 1995.**

2. Dr. Holly Peterson: **Montana Professor of the Year, 1996, by the Carnegie Foundation for the Advancement of Teaching.**

B. Students

1. Tina Donovan: **Outstanding Undergraduate Student in Environmental Engineering, 1997.**

2. Tina Donovan: **Who's Who Among Students in American Universities and Colleges, 1998.**

3. Mazzolini, Dione: **Honorable Mention Research Award at the Boeing Environmental Symposium, 1996.**

4. O'Neill, Susan: **Honorable Mention Research Award at the Boeing Environmental Symposium, 1996.**

5. O'Neill, Susan: **Who's Who Among Students in American Universities and Colleges, 1996.**

X. REPORT OF INVENTIONS

No inventions were obtained during the project.

XI. BIBLIOGRAPHY

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-----, -----, and D. Stock, 1990: Interpretation of measured tracer concentration fluctuations using a sinusoidal meandering plume model. *J. Appl. Meteor.*, **29**, 1284-1299.

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XII. APPENDICES

Table A- 1. Galen 1995 Field Study - Test Conditions

Test	Date	Start Time (MDT)	X (m)	U (m s^{-1})	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} (g min^{-1})
G709t	07-09-95	1902:00	423	3.77	201	11.3	3.4	D	293	2.98
G711m	07-11-95	1630:45	953	1.83	290	12.4	4.7	D	290	5.00
G711p	07-11-95	1724:57	317	3.83	363	19.8	3.7	C	294	3.00
G711s	07-11-95	1817:01	327	2.29	392	26.6	4.3	A	294	4.50
G712e	07-12-95	1315:26	305	4.76	357	13.5	4.3	D	293	3.00
G712k	07-12-95	1521:53	307	3.38	355	11.4	3.5	D	290	3.00
G712m	07-12-95	1547:11	323	4.82	377	17.3	3.9	C	290	4.00
G712o	07-12-95	1611:32	305	5.11	353	10.9	4.0	D	292	4.00
G713b	07-13-95	0519:31	936	1.53	113	11.2	2.1	G	283	0.98

Test code - G: Galen traverse test, S: Galen fixed-point test.

Test durations - 20 min in 1995, 50 min in 1996, and 60 min in 1997.

X - downwind distance.

U - average wind speed.

θ - average wind direction.

σ_θ - standard deviation of horizontal wind fluctuations.

σ_φ - standard deviation of vertical wind fluctuations.

Stability category based on the Sigma-A method (EPA 1987).

T - ambient temperature.

Q_{SF6} - release rate of tracer gas.

Table A- 2. Galen 1996 Field Study – Test Conditions

Test	Date	Start Time (MDT)	X (m)	U (m s^{-1})	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} (g min^{-1})
S712c	07-12-96	1753:00	200	2.87	353	14.7	7.7	D	302	4.00
S712d	07-12-96	1906:00	200	2.55	354	11.8	7.3	D	301	4.00
S712e	07-12-96	2007:00	200	1.58	366	10.1	4.8	D	298	4.00
S806a	08-06-96	1300:00	100	1.58	346	78.6	18.6	A	293	4.00
S806b	08-06-96	1400:05	100	2.17	300	45.4	11.8	A	293	4.00
S806c	08-06-96	1510:00	100	2.42	360	32.5	12.4	A	295	4.00
S806d	08-06-96	1615:00	100	2.02	370	35.6	14.2	A	297	4.00
S806e	08-06-96	1720:00	100	2.52	361	21.2	12.8	B	295	4.00
S806f	08-06-96	1825:00	100	2.96	365	19.3	12.7	C	295	4.00

Test code - G: Galen traverse test, S: Galen fixed-point test.

Test durations - 20 min in 1995, 50 min in 1996, and 60 min in 1997.

X - downwind distance.

U - average wind speed.

θ - average wind direction.

σ_θ - standard deviation of horizontal wind fluctuations.

σ_φ - standard deviation of vertical wind fluctuations.

Stability category based on the Sigma-A method (EPA 1987).

T - ambient temperature.

Q_{SF6} - release rate of tracer gas.

Table A- 3. Galen 1997 Field Study - Test Conditions

Test	Date	Start Time (MDT)	X (m)	U ($m\ s^{-1}$)	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} ($g\ min^{-1}$)
S804c	08-04-97	1746:00	521	1.15	157	36.6	4.7	A	298	10.08
S804d	08-04-97	1906:00	521	1.85	163	55.9	6.6	A	296	10.01
S808c	08-08-97	1530:00	502	4.36	286	18.0	4.5	C	300	11.48
S808d	08-08-97	1638:00	478	4.01	303	18.5	5.2	C	298	11.41
S808e	08-08-97	1741:00	478	3.60	289	20.7	5.3	C	297	11.41
S808g	08-08-97	1924:00	520	4.08	360	11.3	4.8	D	293	11.27
S809b	08-09-97	1606:00	748	4.17	326	13.4	5.4	D	291	11.20
S809c	08-09-97	1713:00	748	4.11	338	15.3	5.3	C	293	11.27
S809d	08-09-97	1819:00	748	3.06	388	51.5	6.5	B	292	11.27
S8010c	08-10-97	1707:00	324	3.45	345	13.6	5.0	D	295	13.79

Test code - G: Galen traverse test, S: Galen fixed-point test.

Test durations - 20 min in 1995, 50 min in 1996, and 60 min in 1997.

X - downwind distance.

U - average wind speed.

θ - average wind direction.

σ_θ - standard deviation of horizontal wind fluctuations.

σ_φ - standard deviation of vertical wind fluctuations.

Stability category based on the Sigma-A method (EPA 1987).

T - ambient temperature.

Q_{SF6} - release rate of tracer gas.

Table A- 4. Boardman Field Study - Test Conditions

Test	Date	Start Time (PST)	X (m)	U (m s^{-1})	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} (g min^{-1})
B275_3	10-01-96	1153:43	203	2.17	70	28.0	17.3	B	292	2.24
B275_4	10-01-96	1234:05	213	2.04	64	26.7	16.2	C	292	2.32
B275_5	10-01-96	1309:10	213	2.14	64	30.8	18.5	B	293	2.31
B275_6	10-01-96	1342:55	213	1.71	65	33.0	18.8	B	293	2.31
B275_7	10-01-96	1423:01	213	1.60	64	31.0	17.4	B	294	2.30
B275_8	10-01-96	1509:57	213	1.38	68	34.4	14.5	A	294	2.30
B275_9	10-01-96	1548:10	149	1.23	66	22.8	15.3	C	294	1.53
B275_10	10-01-96	1628:28	149	1.42	46	18.6	11.6	D	294	1.53
B276_4	10-02-96	1251:14	227	0.95	112	53.7	25.3	A	290	1.82
B276_5	10-02-96	1324:40	227	0.84	82	41.7	22.3	A	291	1.82
B276_7	10-02-96	1434:12	145	0.84	73	31.6	18.8	B	292	0.92

Test code - B: Boardman fixed-point test.

Test durations – 30 min.

X - downwind distance.

U - average wind speed.

θ - average wind direction.

σ_θ - standard deviation of horizontal wind fluctuations.

σ_φ - standard deviation of vertical wind fluctuations.

Stability category based on the Sigma-A method (EPA 1987).

T - ambient temperature.

Q_{SF6} - release rate of tracer gas.

Table A- 5. Observed and Predicted Diffusion Coefficients - Galen Experiments

Test	σ_{yi-mm} (m)	σ_i (m)	σ_i^a (m)	σ_i^b (m)	σ_i^c (m)	σ_i^d (m)	σ_i^e (m)	σ_{yi}^f (m)	σ_{zi}^f (m)	σ_{yi}^g (m)	σ_{zi}^g (m)
G709t	22.5	14.0	18.5	16.0	9.5	9.8	9.8	15.6	10.3	23.8	9.6
G711m	51.1	32.2	46.0	50.0	29.1	31.8	40.9	33.0	18.3	51.2	29.2
G711p	24.9	17.4	24.2	15.1	8.2	8.1	4.9	20.0	21.5	N/C	N/C
G711s	12.3	18.7	33.7	24.6	10.9	10.3	12.7	37.0	58.7	N/C	N/C
G712e	16.0	12.0	16.0	13.3	8.5	8.7	5.0	11.6	8.2	15.0	6.0
G712k	15.9	11.3	14.1	9.8	7.3	7.4	5.4	11.6	8.3	15.2	6.1
G712m	20.8	16.7	21.6	14.3	8.4	8.1	4.9	20.3	21.8	N/C	N/C
G712o	16.6	15.8	12.9	12.4	8.1	8.1	4.3	11.6	8.2	15.0	6.0
G713b	29.3	15.1	40.4	28.6	15.6	14.8	32.8	8.8	3.2	N/C	N/C
S712c	N/A	11.1	11.4	11.1	10.2	10.3	6.5	7.9	6.1	8.2	3.4
S712d	N/A	9.6	9.1	9.7	9.7	9.6	6.5	7.9	6.1	8.2	3.3
S712e	N/A	7.7	7.9	7.8	6.2	6.3	6.4	7.9	6.1	8.2	3.4
S806a	N/A	11.8	31.5	12.7	12.5	8.8	5.2	12.5	23.8	N/C	N/C
S806b	N/A	11.0	17.9	8.6	7.9	6.4	3.4	12.5	23.8	N/C	N/C
S806c	N/A	9.9	12.7	7.6	8.3	7.2	3.3	12.5	23.8	N/C	N/C
S806d	N/A	11.4	13.9	8.6	9.5	8.1	4.1	12.5	23.8	N/C	N/C
S806e	N/A	10.0	8.2	7.1	8.6	7.8	3.3	9.7	15.3	N/C	N/C
S806f	N/A	9.1	7.5	7.9	8.3	8.0	3.4	6.9	9.4	N/C	N/C

σ_{yi-mm} - average horizontal diffusion coefficient from the moment method.

σ_i - average value from the centerline method.

σ_i^a - predicted value from Eq. (1) where $\sigma_i = 0.222\, \sigma_\theta\, x$.

σ_i^b - predicted value from Eq. (2) where $\sigma_i = 0.285\, \sigma_{\theta R}\, x$.

σ_i^c - predicted value from Eq. (3) where $\sigma_i = 0.382\, \sigma_\phi\, x$.

σ_i^d - predicted value from Eq. (4) where $\sigma_i = 0.402\, \sigma_{\phi R}\, x$.

σ_i^e - predicted value from Eq. (5) where $\sigma_i = 0.042\, U^*\, t^{3/2}$.

σ_{yi}^f - predicted horizontal value from Eq. (6) where $\sigma_{yi} = a\, x^b$ with a and b from Turner (1994).

σ_{zi}^f - predicted vertical value from Eq. (7) where $\sigma_{zi} = c\, x^d$ with c and d from Turner (1994).

σ_{yi}^g - predicted horizontal value from the method of Sykes and Gabruk (1997).

σ_{zi}^g - predicted vertical value from the method of Sykes and Gabruk (1997).

N/A – Not Available (because traverse sampling was not performed).

N/C – Not Calculated (because stability category was not near-neutral).

Table A- 6. Observed and Predicted Diffusion Coefficients - Boardman Experiments

Test	σ_I (m)	σ_i^a (m)	σ_i^b (m)	σ_i^c (m)	σ_i^d (m)	σ_i^e (m)	σ_{yi}^f (m)	σ_{zi}^f (m)	σ_{yi}^g (m)	σ_{zi}^g (m)
B275_3	23.3	21.9	26.3	23.3	23.3	17.4	18.6	25.6	38.5	17.4
B275_4	23.2	22.2	25.5	23.1	23.2	17.2	13.9	16.1	42.5	15.2
B275_5	23.5	25.5	29.2	26.4	25.6	20.0	19.4	26.5	48.2	17
B275_6	32.7	27.7	30.9	27.1	26.4	22.9	19.4	26.5	45.8	16.1
B275_7	26.3	25.6	27.5	24.6	24.8	21.8	19.4	26.5	50.6	15.9
B275_8	26.7	20.1	22.3	20.6	20.9	20.2	25.0	42.4	40.6	13.1
B275_9	25.8	13.1	13.7	15.2	14.6	12.7	10.0	12.5	28.2	3.8
B275_10	22.1	10.7	11.1	11.5	11.4	10.7	6.0	5.0	20.0	8.8
B276_4	30.5	47.2	43.1	38.2	35.8	30.7	26.5	44.5	61.8	19.8
B276_5	32.2	36.6	43.0	33.7	34.6	38.2	26.5	44.5	48.5	24.8
B276_7	27.7	13.7	13.3	12.9	12.0	11.5	13.6	20.0	20.4	7.5

Table A- 7. Observed and Predicted Concentration Fluctuation Statistics for the 1996 and 1997 Galen Tests Using Equation 1 in the MIND Model.

Test	$(C \pm \sigma c)^O$	$(C \pm \sigma c)^P$	P^O	P^P	P/M^O	P/M^P	I^O	I^P	In^O	In^P
S712c	2095 ± 3187	3566 ± 4470	12106	17081	4.17	4.79	0.61	0.80	1.10	1.25
S712d	4999 ± 4162	7527 ± 7583	18248	29505	3.65	3.92	0.81	0.92	0.83	1.01
S712e	1135 ± 5036	1674 ± 7185	44468	54891	39.17	32.79	0.08	0.29	4.44	4.29
S806b	450 ± 1524	1180 ± 2157	15544	12932	34.56	10.96	0.20	0.45	3.39	1.83
S806c	1727 ± 2957	2316 ± 3441	17513	25269	10.14	10.91	0.49	0.61	1.71	1.49
S806d	1377 ± 2837	1615 ± 3167	16093	34564	11.68	21.40	0.39	0.48	2.06	1.96
S806e	1763 ± 3218	2374 ± 5154	16318	30503	9.26	12.85	0.40	0.50	1.83	2.17
S806f	905 ± 2373	382 ± 1852	17160	24431	19.00	63.98	0.27	0.21	2.62	4.85
S804c	530 ± 1867	221 ± 467	13723	1874	25.89	8.49	0.35	0.38	3.52	2.11
S804d	2622 ± 4987	175 ± 256	19661	2184	7.50	12.50	0.43	0.52	1.90	1.47
S808c	603 ± 1243	535 ± 708	8268	3312	13.72	6.19	0.47	0.63	2.06	1.32
S808d	465 ± 1043	321 ± 713	6652	3177	14.09	9.89	0.28	0.28	2.24	2.22
S808e	1477 ± 2164	718 ± 860	9986	4815	6.76	6.71	0.66	0.71	1.47	1.20
S808g	1361 ± 1688	1148 ± 1791	6927	7312	5.09	6.37	0.65	0.59	1.24	1.56
S809b	221 ± 396	566 ± 608	2374	2038	10.72	3.60	0.39	0.72	1.79	1.07
S809c	322 ± 707	302 ± 417	5096	1966	15.85	6.52	0.36	0.65	2.20	1.38
S809d	667 ± 1275	40 ± 50	6855	140	10.27	3.48	0.38	0.42	1.91	1.23
S810c	1025 + 1674	2268 ± 3960	8887	16622	8.67	7.33	0.51	0.54	1.63	1.75

$(C \pm \sigma c)^O$ = Observed mean concentration and concentration standard deviation (ppt).
$(C \pm \sigma c)^P$ = Predicted mean concentration and concentration standard deviation (ppt).
P^O = Observed peak concentration (ppt).
P^P = Predicted peak concentration (ppt).
P/M^O = Observed peak-to-mean ratio.
P/M^P = Predicted peak-to-mean ratio.
I^O = Observed intermittency factor.
I^P = Predicted intermittency factor.
In^O = Observed intensity.
In^P = Predicted intensity.

Table A- 8. Observed and Predicted Concentration Fluctuation Statistics for the 1996 and 1997 Galen Tests Using Equation 2 in the MIND Model.

Test	$(C \pm \sigma c)^{O}$	$(C \pm \sigma c)^{P}$	P^{O}	P^{P}	P/M^{O}	P/M^{P}	I^{O}	I^{P}	In^{O}	In^{P}
S712c	2095 ± 3187	3566 ± 4470	12106	17081	4.17	4.79	0.61	0.80	1.10	1.25
S712d	4999 ± 4162	7527 ± 7583	18248	29505	3.65	3.92	0.81	0.92	0.83	1.01
S712e	1135 ± 5036	1674 ± 7185	44468	54891	39.17	32.79	0.08	0.29	4.44	4.29
S806b	450 ± 1524	1180 ± 2157	15544	12932	34.56	10.96	0.20	0.45	3.39	1.83
S806c	1727 ± 2957	2316 ± 3441	17513	25269	10.14	10.91	0.49	0.61	1.71	1.49
S806d	1377 ± 2837	1615 ± 3167	16093	34564	11.68	21.40	0.39	0.48	2.06	1.96
S806e	1763 ± 3218	2374 ± 5154	16318	30503	9.26	12.85	0.40	0.50	1.83	2.17
S806f	905 ± 2373	382 ± 1852	17160	24431	19.00	63.98	0.27	0.21	2.62	4.85
S804c	530 ± 1867	221 ± 467	13723	1874	25.89	8.49	0.35	0.38	3.52	2.11
S804d	2622 ± 4987	175 ± 256	19661	2184	7.50	12.50	0.43	0.52	1.90	1.47
S808c	603 ± 1243	535 ± 708	8268	3312	13.72	6.19	0.47	0.63	2.06	1.32
S808d	465 ± 1043	321 ± 713	6652	3177	14.09	9.89	0.28	0.28	2.24	2.22
S808e	1477 ± 2164	718 ± 860	9986	4815	6.76	6.71	0.66	0.71	1.47	1.20
S808g	1361 ± 1688	1148 ± 1791	6927	7312	5.09	6.37	0.65	0.59	1.24	1.56
S809b	221 ± 396	566 ± 608	2374	2038	10.72	3.60	0.39	0.72	1.79	1.07
S809c	322 ± 707	302 ± 417	5096	1966	15.85	6.52	0.36	0.65	2.20	1.38
S809d	667 ± 1275	40 ± 50	6855	140	10.27	3.48	0.38	0.42	1.91	1.23
S810c	1025 ± 1674	2268 ± 3960	8887	16622	8.67	7.33	0.51	0.54	1.63	1.75

Table A- 9. Observed and Predicted Concentration Fluctuation Statistics for the 1996 and 1997 Galen Tests Using Equation 3 in the MIND Model.

Test	$(C \pm \sigma_C)^O$	$(C \pm \sigma_C)^P$	P^O	P^P	P/M^O	P/M^P	I^O	I^P	In^O	In^P
S712c	2095 ± 3187	1664 ± 3356	12106	16927	4.17	10.17	0.61	0.45	1.10	2.02
S712d	4999 ± 4162	7151 ± 6801	18248	26389	3.65	3.69	0.81	0.93	0.83	0.95
S712e	1135 ± 5036	1844 ± 9068	44468	80680	39.17	43.74	0.08	0.15	4.44	4.92
S806b	450 ± 1524	2986 ± 8127	15544	50402	34.56	16.88	0.20	0.25	3.39	2.72
S806c	1727 ± 2957	3441 ± 6768	17513	57987	10.14	16.85	0.49	0.49	1.71	1.97
S806d	1377 ± 2837	2122 ± 5376	16093	72339	11.68	34.09	0.39	0.36	2.06	2.53
S806e	1763 ± 3218	2320 ± 4856	16318	28240	9.26	12.17	0.40	0.52	1.83	2.09
S806f	905 ± 2373	409 ± 1725	17160	20116	19.00	49.21	0.27	0.27	2.62	4.22
S804c	530 ± 1867	1106 ± 5353	13723	39074	25.89	35.33	0.35	0.08	3.52	4.84
S804d	2622 ± 4987	1380 ± 2929	19661	34442	7.50	24.95	0.43	0.27	1.90	2.12
S808c	603 ± 1243	1085 ± 2614	8268	17792	13.72	16.40	0.47	0.36	2.06	2.41
S808d	465 ± 1043	597 ± 1917	6652	11625	14.09	19.46	0.28	0.19	2.24	3.21
S808e	1477 ± 2164	1772 ± 3401	9986	24614	6.76	13.89	0.66	0.47	1.47	1.92
S808g	1361 ± 1688	1587 ± 3053	6927	13476	5.09	8.49	0.65	0.48	1.24	1.92
S809b	221 ± 396	881 ± 1196	2374	4231	10.72	4.80	0.39	0.60	1.79	1.36
S809c	322 ± 707	465 ± 986	5096	5607	15.85	12.07	0.36	0.42	2.20	2.12
S809d	667 ± 1275	430 ± 795	6855	2860	10.27	6.65	0.38	0.38	1.91	1.85
S810c	1025 + 1674	3707 + 8603	8887	42337	8.67	11.42	0.51	0.37	1.63	2.32

Table A- 10. Observed and Predicted Concentration Fluctuation Statistics for the 1996 and 1997 Galen Tests Using Equation 4 in the MIND Model.

Test	$(C \pm \sigma_C)^O$	$(C \pm \sigma_C)^P$	P^O	P^P	P/M^O	P/M^P	I^O	I^P	In^O	In^P
S712c	2095 ± 3187	4000 ± 5450	12106	21200	4.17	5.30	0.61	0.77	1.10	1.36
S712d	4999 ± 4162	7187 ± 6872	18248	26663	3.65	3.71	0.81	0.92	0.83	0.96
S712e	1135 ± 5036	1858 ± 9245	44468	83364	39.17	44.87	0.08	0.15	4.44	4.98
S806b	450 ± 1524	3898 ± 11448	15544	74996	34.56	19.24	0.20	0.20	3.39	2.94
S806c	1727 ± 2957	3983 ± 8530	17513	77276	10.14	19.40	0.49	0.45	1.71	2.14
S806d	1377 ± 2837	2357 ± 6783	16093	99640	11.68	42.28	0.39	0.30	2.06	2.88
S806e	1763 ± 3218	2454 ± 5617	16318	34090	9.26	13.89	0.40	0.48	1.83	2.29
S806f	905 ± 2373	401 ± 1761	17160	21270	19.00	53.06	0.27	0.25	2.62	4.39
S804c	530 ± 1867	1383 ± 7415	13723	60192	25.89	43.53	0.35	0.07	3.52	5.36
S804d	2622 ± 4987	3623 ± 9128	19661	129589	7.50	35.77	0.43	0.22	1.90	2.52
S808c	603 ± 1243	1075 ± 2560	8268	17285	13.72	16.08	0.47	0.37	2.06	2.38
S808d	465 ± 1043	596 ± 1910	6652	11571	14.09	19.41	0.28	0.19	2.24	3.20
S808e	1477 ± 2164	1809 ± 3518	9986	25651	6.76	14.18	0.66	0.46	1.47	1.94
S808g	1361 ± 1688	1592 ± 3067	6927	13546	5.09	8.51	0.65	0.48	1.24	1.93
S809b	221 ± 396	862 ± 1157	2374	4069	10.72	4.72	0.39	0.61	1.79	1.34
S809c	322 ± 707	461 ± 973	5096	5517	15.85	11.96	0.36	0.42	2.20	2.11
S809d	667 ± 1275	474 ± 911	6855	3334	10.27	7.03	0.38	0.38	1.91	1.92
S810c	1025 + 1674	3699 ± 8574	8887	42173	8.67	11.40	0.51	0.37	1.63	2.32

Table A- 11. Observed and Predicted Concentration Fluctuation Statistics for the 1996 and 1997 Galen Tests Using Equation 5 in the MIND Model.

Test	$(C \pm \sigma c)^O$	$(C \pm \sigma c)^P$	P^O	P^P	P/M^O	P/M^P	I^O	I^P	In^O	In^P
S712c	2095 ± 3187	6603 ± 12212	12106	52954	4.17	8.02	0.61	0.54	1.10	1.85
S712d	4999 ± 4162	9969 ± 14047	18248	58021	3.65	5.82	0.81	0.83	0.83	1.41
S712e	1135 ± 5036	1854 ± 9187	44468	82484	39.17	44.50	0.08	0.15	4.44	4.96
S806b	450 ± 1524	8583 ± 31181	15544	250889	34.56	29.23	0.20	0.13	3.39	3.63
S806c	1727 ± 2957	9122 ± 29026	17513	331852	10.14	36.38	0.49	0.21	1.71	3.18
S806d	1377 ± 2837	3637 ± 18118	16093	341666	11.68	93.93	0.39	0.17	2.06	4.98
S806e	1763 ± 3218	4821 ± 21671	16318	187442	9.26	38.88	0.40	0.17	1.83	4.50
S806f	905 ± 2373	234 ± 3636	17160	111782	19.00	478.09	0.27	0.04	2.62	15.55
S804c	530 ± 1867	786 ± 3274	13723	20536	25.89	26.14	0.35	0.10	3.52	4.17
S804d	2622 ± 4987	2681 ± 6369	19661	84970	7.50	31.69	0.43	0.23	1.90	2.38
S808c	603 ± 1243	1219 ± 3442	8268	25803	13.72	21.16	0.47	0.32	2.06	2.82
S808d	465 ± 1043	706 ± 2590	6652	17250	14.09	24.44	0.28	0.17	2.24	3.67
S808e	1477 ± 2164	2111 ± 4543	9986	35167	6.76	16.66	0.66	0.42	1.47	2.15
S808g	1361 ± 1688	1907 ± 4056	6927	18746	5.09	9.83	0.65	0.44	1.24	2.13
S809b	221 ± 396	837 ± 1106	2374	3874	10.72	4.63	0.39	0.62	1.79	1.32
S809c	322 ± 707	459 ± 964	5096	5453	15.85	11.88	0.36	0.43	2.20	2.10
S809d	667 ± 1275	415 ± 757	6855	2701	10.27	6.51	0.38	0.38	1.91	1.82
S810c	1025 + 1674	5087 ± 13900	8887	76293	8.67	15.00	0.51	0.28	1.63	2.73